Diagnostics Comparing Sea Surface Temperature Feedbacks from Operational Hurricane Forecasts to Observations

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Manuscript submitted 8 April 2011

This paper examines the ability of recent versions of the Geophysical Fluid Dynamics Laboratory Operational Hurricane Forecast Model (GHM) to reproduce the observed relationship between hurricane intensity and hurricane-induced Sea Surface Temperature (SST) cooling. The analysis was performed by taking a lagrangian composite of all hurricanes in the North Atlantic from 1998-2009 in observations and 2005-2009 for the GHM. A marked improvement in the intensity-SST relationship for the GHM compared to observations was found between the years 2005 and 2006-2009 due to the introduction of warm-core eddies, a representation of the loop current, and changes to the drag coefficient parameterization for bulk turbulent flux computation. A Conceptual Hurricane Intensity Model illustrates the essential steady-state characteristics of the intensity-SST relationship and is explained by two coupled equations for the atmosphere and ocean. The conceptual model qualitatively matches observations and the 2006-2009 period in the GHM, and is used to support results showing that weaker upper oceanic thermal stratification in the Gulf of Mexico, caused by the introduction of the loop current and warm core eddies, is crucial to explaining the observed SST-intensity pattern. The diagnostics proposed by the conceptual model offer an independent set of metrics for comparing operational hurricane forecast models to observations.

1. Introduction

The ongoing development of operational hurricane forecasts is an important endeavor for scientific, economic, and societal reasons. Over the last decade, significant improvements have been made to predictions of hurricane track and intensity in statistical and dynamical operational models [e.g., Bender et al., 2007; DeMaria et al., 2005; Gopalakrishnan et al., 2010]. In these dynamical models, improvements have been centered on alterations to model physics, through the inclusion of ocean coupling, convective parameterizations, air-sea flux schemes, and numerical resolution. Ocean coupling, in particular, has brought large improvements to model intensity forecasts [Bender and Ginis, 2000], owing to the influence of hurricane induced Sea Surface Temperature (SST) changes on intensity.

The strength of operational hurricane forecast models can and should be tested against their ability to simulate a broad range of observations. Past studies, which compare forecast models to observations, have tended to focus on comparing individual case studies of notable hurricanes when examining the oceanic response [e.g., Bender and Ginis, 2000]. It is also useful to compare forecast model results to observations for a large number of hurricanes over a full range of intensities, in order to better assess model errors, identify the character of systematic biases, and help guide efforts to improve the sources of model error.

In this paper we attempt to develop these diagnostics for the particular case of the SST response to hurricanes for different intensities. We focus on results from the Geophysical Fluid Dynamical Laboratory (GFDL) Hurricane Model (GHM) and seek to compare observations to past operational forecasts, for a large number of hurricanes stratified by intensity on the Saffir-Simpson scale. The representation of hurricane intensity in the GHM (and others) is often too weak for the most intense hurricanes when compared to observations (Bender et. al. 2000), for which several reasons deserve comment. First, there may be deficiencies in model physics, and the simulation of hurricanes may be limited by the existence of physical processes that are not fully understood. Second, the model resolution (1/12° at the core) could be too coarse to simulate hurricanes with the required accuracy. The final reason, which is the chief concern of this paper and relates to the previous two, is that the ocean-atmosphere coupling may not be realistic.

The diagnostics presented here are used for the GHM but they could be applied to any forecast model or any General Circulation Model with reasonable tropical cyclone simulations. The results place emphasis on

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the SST-intensity relationship, since it has been shown in both observations and models that the influence of oceanic feedback is important to hurricanes [Schade and Emanuel, 1999; Bender and Ginis, 2000; Knutson et al., 2001; Cione and Uhlhorn, 2003; Kaplan and DeMaria, 2003; Shen and Ginis, 2003; Lloyd and Vecchi, 2011] and that, as a consequence, large-scale ocean conditions may be important for constraining hurricane intensity. In this study, comparisons are made with observations of SST over a twelve-year period to help clarify whether oceanic feedback is suitably depicted in the GHM.

Finally, to reinforce the connections between observations and the GHM, we present a simplified conceptual framework for understanding ocean-atmosphere interaction during the lifecycle of a tropical cyclone. The Conceptual Hurricane Intensity Model does not hold any dynamical equations, but offers a simplified framework for understanding the SST-intensity relationship and provides general metrics for comparing observations to forecast models.

Our aim is to motivate an additional set of diagnostics that could expand the types of analyses pursued by the hurricane forecast community in the development of models, in the pursuit of better identifying deficiencies in model physics and improving operational forecasts.

The remainder of this paper is divided as follows: Methods and data are presented in Section 2; results are shown in Section 3, comparing observations to the GHM for the periods 2005 and 2006-2009; the conceptual hurricane intensity model is presented and discussed in Section 4, which offers diagnostics for evaluating the SST-intensity relationship; and Section 5 concludes.

2. Methods and Data

2.1. Observational datasets

The Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) sensor allows for daily observations of SST even under clouds [Wentz et al., 2000], and has led to new insights into air-sea interaction processes [Xie et al., 1998; Chelton et al., 2001; Lloyd and Vecchi, 2011]. We use observations from the TMI satellite to examine the SST response along tropical cyclone tracks over the period 1998-2009. Anomalies of SST are computed from a monthly climatology based on 1998-2009.

We average the data from TMI-SST using the positions of North Atlantic tropical cyclones from the IBTRACS tropical cyclone dataset [Knapp et al., 2009] to generate Lagrangian composite response for 12 years of tropical cyclones (see Section 2.3). The IBTRACS dataset records the 10-minute maximum wind speed along with tropical cyclone track locations at six hour intervals, which we convert to 1-minute values by dividing by 0.88 [Knapp et al., 2009]. This conversion allows wind speeds from IBTRACS data to be compared on the Saffir-Simpson scale, which uses a 1-minute maximum wind speed definition.

2.2. GFDL Forecast Model (GHM)

Hurricane forecast data are analyzed in the coupled GFDL Hurricane Model [hereafter GHM; Kurihara et al., 1998; Bender et al., 2007] over the period 2005-2009. The GHM consists of a triply nested system, with maximum resolution of 1/12° at the storm center. The model domain spans a 75° x 75° area, from 15°S-60°N, with the innermost grid able to relocate in the east-west direction over the North Atlantic. The location of the innermost grid is a function of the initial hurricane location and the hurricane's subsequent coordinates during the forecast. The atmospheric model is governed by primitive equations with hydrostatic balance, and contains 42 vertical levels. The atmosphere is coupled to the Princeton Ocean Model [Blumberg and Mellor, 1987; Ezer and Mellor, 1997], which includes full ocean dynamics, a vertical sigma coordinate system, and a free surface. The Forecast Model is initialized with real-time data from the NCEP Global Forecast System [GFS; Sela, 1980; Environmental Modeling Center, 2003], with the hurricane vortex initialized using an axisymmetric version of the GHM [Bender et al., 2007]. Through the forecast period the model produces a net ocean cooling bias, as over the 126 hour forecast, the ocean receives no incoming solar radiation (Morris Bender, pers. comm.). Consequently there is a net SST cooling of the entire domain by approximately 0.4K over the forecast period.

A number of improvements have been introduced to the model since its creation. In particular, prior to 2006, the Arakawa-Schubert convection scheme [Arakawa and Schubert, 1974] was introduced in 2003, and grid resolution in the innermost nest was doubled to 1/2° resolution in 2005. From the year 2006 and onwards three major changes were made to the GHM: a representation of the Gulf of Mexico loop current and warm core eddies was introduced [Bender et al., 2007; Yablonsky and Ginis, 2008]; the large-scale condensation scheme was replaced with the Ferrier cloud microphysics package in 2006 [Ferrier, 2005]; and the drag coefficient parameterization of Large and Pond [1981], for which the drag coefficient is proportional to intensity, was replaced by the Moon et al. [2004] scheme, in which the drag coefficient tends to a constant value at high intensities. Thus the drag coefficient in 2005 is larger at higher intensities than in 2006-2009 (see Bender et al. [2007], Figure 2). To evaluate the impact of the changes to model physics in 2006, we focus on comparing the period 2006-2009 to the year 2005. Despite comparing the single year, 2005, to a four-year period, the North Atlantic hurricane season was very active and produced a significant amount of data in comparison to 2006-2009, providing multiple cases to compare.

For each Atlantic hurricane, one forecast was performed with the GHM every six hours. Each forecast runs for 126 hours (5.25 days), with data being recorded at six-hour intervals, so that each forecast contains 22 lead times (including initialization at $t = 0$). Forecast tracks for 2005-2009 are shown in Figure 1.

For the periods 2005 and 2006-2009, 1° x 1° averaged SST data and maximum 1-minute wind speeds were used to diagnose every hurricane forecast. In order to estimate the cyclone induced SST response we build on the methods of Lloyd and Vecchi [2011], and compare the SST two days after hurricane passage to the SST two days before hurricane passage over a fixed location. We denote this cyclone-induced change in SST as ΔSST.

At every six-hour interval during a forecast, the GHM saves SST values across the model domain. In order to measure ΔSST, the sample of forecast points must contain data that extends ± 2 days at the time of the forecast. As a result, it is only possible to measure ΔSST in the forecast window from 48-78 hours, representing six data points (out of the 0-126 hours for the total forecast). While we can only estimate a subset of forecast points, each forecast still contains six times more data than one observational point. Forecast data north of 35°N are excluded in order to remove extra-tropical cyclones from the analyses.

2.3. Lagrangian Composite Method

Our principle diagnostic technique builds on the lagrangian composite analysis of Lloyd and Vecchi [2011]. The lagrangian composite analysis was performed over 2,489 tropical cyclone track locations in the North Atlantic for observations, and 11,003 forecast track locations in the GHM. In this approach, evaluation of the SST was made before, during, and after a tropical cyclone passes every recorded position for all tropical cyclone tracks. The TMI-SST data were sampled at daily intervals for 1° x 1° areas centered on the tropical cyclone track location, while the GHM SST data were sampled at six-hour intervals for 1° x 1° regions.

A composite response was calculated by averaging SST and intensity over all track positions for all hurricanes, in both observations and the GHM. The composite response was computed separately by category on the Saffir-Simpson scale, according to the magnitude of the maximum wind speed, and was also stratified using the criteria V/f, for the tropical cyclones translation speed V divided by the coriolis parameter f. A threshold criteria of $V/f = 1$, where 1 unit = 100 km, was used to prescribe approximately equal numbers of fast moving (or low latitude) tropical cyclones for $V/f < 1$, and slow moving (or high latitude) tropical cyclones for $V/f > 1$. We focus on the criteria $V/f < 1$ because under these conditions there is an enhanced role for ocean feedback (Lloyd and Vecchi, 2011). For category 0 tropical cyclones, tropical depressions with maximum wind speeds of $17ms^{-1}$ or less were excluded. To examine the composite mean response two days after the passage of the tropical cyclone, Normal statistics were used to estimate the uncertainty k in the sample mean $\overline{x}$, for true mean $\mu = \overline{x} \pm k$. The uncertainty in the composite mean is given by $k = \frac{st_{\alpha/2}}{\sqrt{n}}$ where s is the sample standard deviation, n is the number of tropical cyclone track points, and $t_{\alpha/2}$ is the t-statistic with significance level α, which was set to the 90% and 95% confidence intervals.

To examine the effect of the Gulf of Mexico loop current and warm core eddies from 2006 onwards in the GHM, the SST-intensity response was subdivided into geographic regions from 100°W - 80°W (Gulf of Mexico) and 80°W - 0°W. Hurricanes were are also divided into two classes (intensifying and decaying) based on the tendency of their intensity, in both observations and the GHM. The average intensity tendency dI/dt over a 36 hour period (containing six data points) starting at day 0 was used to define intensifying or decaying tropical cyclones, such that $dI/dt > 0$ for growing tropical cyclones, and $dI/dt < 0$ for decaying tropical cyclones. Tropical cyclones reaching landfall within the 36 hour period were excluded from either classification, in both observations and the GHM. In addition to examining the SST cooling for a given intensification or decay phase, tropical cyclones were divided into different bands of SST cooling, at 1K intervals, to examine the fraction of tropical cyclones that grow or decay for a given band of cooling.

3. Results

The frequency distribution of hurricane intensities indicates a closer correspondence between observations and the GHM for 2006-2009 compared to 2005, particularly at higher intensities (Figure 2). In 2005 there were no GHM forecasts that exceeded $70ms^{-1}$, while observations exceeded $80ms^{-1}$. After changes to model physics for 2006-2009 the GHM forecast intensity reached the $75-80ms^{-1}$ range, in closer agreement with observations.

The hurricane-induced SST response as a function of time, for a Lagrangian composite over all hurricanes, peaks over days +1 to +2 in observations and the GHM (Figure 3). For the GHM compared to observations in 2005, the hurricane-induced SST cooling is too large for Categories 1, 3, and 4, while there are no category 5's and tropical storms do not induce a realistic SST response. Although there were three observed category 5 hurricanes in 2005, there were no category 5's in the forecast model during the forecast from hours 48-78 over which the analysis is computed, for the criteria $V/f < 1$. For 2006-2009, the maximum forecast SST cooling for category 1-3 is similar to observations for 1998-2009 (Figure 3). In comparing 2006-2009 GHM forecasts to observations it is preferable to extend the observational period beyond these years, in order to obtain significant analysis for high intensity hurricanes. Observations from 1998-2009 are thus used, because in each year the GHM contains approximately 20 times more hurricane data points through the successive forecasts during the lifecycle of each hurricane.

In observations, the hurricane induced SST-intensity response levels off with increasing intensity for each of the periods 2005, 2006-2009, and 1998-2009 for the criteria $V/f < 1$ (Figure 4). For the GHM however, the SST-intensity response is monotonic in 2005 (even though there are no category 5 hurricanes with $V/f < 1$). Forecast results from the period 2006-2009 show greater similarity with observations from 1998-2009, with forecast SST cooling peaking at category 2 and becoming smaller in magnitude up to category 5.

Lloyd and Vecchi [2011] found that in the North Atlantic, hurricanes exhibit a non-monotonic SST-intensity relationship, which was interpreted as indicating the systematic importance of an oceanic feedback over hurricane intensity, and hence the importance of large-scale oceanic conditions on hurricane intensity. A monotonic SST-intensity relationship in the GHM, for 2005, could indicate that oceanic feedback is too weak compared to atmospheric drivers of intensity, or that ocean stratification – by which we refer to upper ocean thermal structure – is inadequately represented. With the introduction in 2006 of the initialization of warm-core eddies into the GHM, a representation of the loop current, and improvements to the drag coefficient parameterization, the SST-intensity response appears to be more non-monotonic in nature, showing greater similarity to observations. Given this result, the remaining analyses focus on the period 2006-2009 in the GHM as it most closely simulates observations.

For different hurricane translation speeds in the GHM (Figures 5.a and 5.c), the cyclone induced cooling is larger for slow translation speeds (or high latitudes) with $V/f < 1$, with smaller cooling for fast translation speeds (or low latitudes) for $V/f > 1$. This result is comparable to observations (Figures 6.a and 6.c, modified from Lloyd and Vecchi [2011] to cover the period 1998-2009), in that the SST-intensity relationship for $V/f < 1$ is non-monotonic in nature, showing the effect of ocean-atmosphere coupling, while for $V/f > 1$ the relationship is monotonic, driven by atmospheric forcing. For weakening hurricanes ($\Delta I < 0$), there is some evidence of larger SST cooling and greater non-monotonicity than for intensifying hurricanes ($\Delta I > 0$; Figures 5.b and 5.d), but the contrast between intensifying and decaying hurricanes is less pronounced than in observations (Figures 6.b and 6.d) indicating reduced sensitivity to oceanic feedback.

The intensity tendency, dI/dt, indicating intensification and decay, is not significantly different when comparing observations from 1998-2009 with the GHM from 2006-2009 across different bands of SST cooling (not shown). Thus further inferences cannot be made until the uncertainty is reduced, for instance by analyzing a longer record (for diagnosis of intensity tendency in observations, see Lloyd and Vecchi [2011], Figure 7).

Dividing the GHM SST-intensity response into the geographic regions 100°W - 80°W (Gulf of Mexico) and 80°W - 0°W (east of 80°W) highlights the effect of including a representation of the loop current and warm core eddies in the Gulf of Mexico from 2006 onwards (Figure 7). For the Gulf of Mexico region there is a significant reduction in SST cooling across hurricane categories for 2006-2009 compared to 2005. For the region east of 80°W, the difference in the SST-intensity response before and after the changes to model physics is significantly smaller. Because changes in model physics for the drag coefficient parameterization and cloud microphysics are uniformly employed across the model domain, the larger change in SST-intensity response in the Gulf of Mexico can be attributed to the new representation of loop current and warm core eddies. Thus, the largest contribution to changes in the SST-intensity response in the GHM after 2006 is due to oceanic changes that produce weaker upper oceanic thermal stratification in the Gulf of Mexico. This result is supported by Yablonsky and Ginis [2008] who examine oceanic heat content in the Gulf of Mexico before and after 2006 and compare the GHM to observations (from XBTs; see Yablonsky and Ginis [2008], Figure 13).

4. Conceptual Hurricane Intensity Model

In clarifying the role of ocean feedback in the SST-intensity response, and developing quantitative metrics to compare observations and the GHM, it is helpful to consider a conceptual framework by making a number of simplifying assumptions to emphasize the basic ocean-atmosphere coupled phenomena. We are not aiming here for exact numerical results; rather, our philosophy is to seek a broad description of the SST-intensity behavior without exact precision, using the most simple framework possible. There are no dynamical equations in the model, and it is comparable to conceptual models of the El Niño Southern Oscillation such as the recharge-discharge oscillator [Jin, 1997]. Additional layers of complexity could be added [see, for example, Schade and Emanuel, 1999], but we do not, as increased complexity calls for the addition of more parameters, creating extra biases and sources of error. Using observations to constrain parameters in this framework provides another measure by which to test the GHM.

Primarily we assume that hurricanes move with fixed storm radii following a Rankine vortex structure, hold constant translation speed, and are axisymmetric (See Appendix A). We do not explicitly account for the influence of vertical wind shear, or other dynamical atmospheric conditions that influence storms' intensification. Our starting point is that hurricane intensity varies according to:

$$\frac{\partial I}{\partial t} = \alpha(I^* - I) \tag{4.1}$$

Where I^* is the maximum potential intensity (ms^{-1}), I is the hurricane intensity (ms^{-1}), t represents time (days), and α is a hurricane intensity growth term (days^{-1}). This potential intensity could be, but is not confined to, the Emanuel [1988] potential intensity. However, a theoretical or empirical measure representing the true value of maximum hurricane intensity could represent I^*. This measure of I^* could take into account vertical wind shear or other parameters [e.g., Tang and Emanuel, 2010]. To first order, we assume that hurricane potential intensity can be linearized as follows:

$$I^* = \tilde{I}^* - \beta T \tag{4.2}$$

Where $\tilde{I}^*$ represents the pre-storm potential intensity (ms^{-1}) – that is, the potential intensity before passage of a hurricane over a particular location – which could, for instance, be taken at day -2. The term T represents the magnitude of hurricane-induced SST cooling (K) two days after hurricane passage over a fixed location. The constant linearization term β ($ms^{-1}K^{-1}$) represents the reduction in intensity for one degree of SST cooling. Based on the sensitivity of potential intensity to changes in localized SST in General Circulation Models, we use the estimate $\beta \approx 8.2ms^{-1}K^{-1}$ from Vecchi and Soden [2007].

We couple Equation 1 for the atmosphere to a very simple oceanic equation, showing the response to cyclone forcing and subsequent recovery:

$$\frac{\partial T}{\partial t} = \mu I - \epsilon T \tag{4.3}$$

The oceanic sensitivity parameter μ should scale in proportion to upper oceanic thermal stratification, and is in units of Km^{-1}. The ϵT term represents a restoring term with an e-folding time ϵ^{-1}, where ϵ is in units of days^{-1}. Results from the model are shown for steady-state response at a relatively slow translation speed of $2.3ms^{-1}$. Further explanation of the Conceptual Hurricane Intensity Model and calculation of parameters in the model are given in Appendix A and B, respectively.

Scatter plots showing the hurricane-induced SST response versus intensity are presented in Figure 8 for the conceptual model, the GHM for 2006-2009, and observations for 1998-2009. While the numerical values in the conceptual model are only correct to an approximate order of magnitude, the non-monotonic nature of the SST-intensity response is evident (Figure 8.c). In the conceptual model there are two regimes. First, below the critical intensity value at which the SST response is maximum, hurricane growth is driven by atmospheric conditions manifested through the difference between pre-storm potential intensity $\tilde{I}$* and the actual intensity I. In this first regime, the Intensity-SST relationship follows lines of constant oceanic sensitivity μ, and the negative gradient is given as $-\mu/\epsilon$. In the second regime, I approaches the $\tilde{I}$*-limit and further intensification to the very largest values (category 4 and 5) can only occur if the oceanic sensitivity μ can vary and become small, so that upper oceanic thermal stratification is weak and oceanic feedback is restricted. In this second regime, the positive gradient giving the overall non-monotonic response is determined by $+1/\beta$. In the case of $\beta = 0$ (no oceanic feedback) the second regime has an infinite slope, and the SST-intensity response is monotonic and driven by atmospheric forcing (not shown). Thus, the conceptual model offers measures of oceanic sensitivity μ and oceanic-feedback β in the steady state, and estimation of these parameters provide an independent test of hurricane forecast model performance compared to observations.

In this study we compare the two linear gradients for the SST-intensity relationship outlined by the conceptual model for observations from 1998-2009 and the GHM for 2005 and 2006-2009. The first regime is determined by Gradient I, for the Intensity-SST response below maximum SST cooling between Categories 2-3. The second regime, characterized by Gradient II, is for higher intensities beyond the point of maximum SST cooling (see Figure 8). To determine Gradients I and II, we take regression slopes from the 95th percentile of SST-intensity data, using $5ms^{-1}$ intervals. In both cases Gradient I is calculated from $15 - 45ms^{-1}$. The use of $5ms^{-1}$ intervals is more accurate, as the Saffir-Simpson definition contains intensity intervals of different sizes. A summary of gradients for the 90th percentile in the two regimes is given in Table 1, with slope errors indicated by the 95% confidence intervals.

Under the conceptual model framework, the 2006-2009 GHM period corresponds closely to observations, and captures the essence of both regimes: the first for increased SST cooling with intensity under atmospheric drivers, and the second for reduced SST cooling with intensity, reflecting weaker oceanic stratification in the Gulf of Mexico and, hence, reduced oceanic feedback allowing for intensification to category 4 and 5 hurricanes. The 2006-2009 period is in strong contrast to 2005 in the GHM, because despite Gradient I values being comparable, the second regime does not exist in 2005, and there are no category 5 hurricanes. The absence of the second regime in 2005 is likely to be due to two factors. First, a reduced potential intensity I^* may prevent hurricanes from reaching observed intensities (Figure 2). Second, a larger oceanic sensitivity μ in the Gulf of Mexico may prevent further intensification after hurricanes have reached their $\tilde{I}$*-limit and enter the second regime of the conceptual model.

The conceptual model highlights the difference between the years 2005 and 2006-2009 in the GHM, for which larger I^* and lower values of ocean sensitivity μ in the Gulf of Mexico (Figure 7) produces a response that is qualitatively similar to the observed SST-relationship (Figures 8.c, 8.d, and 8.e). The year 2005 is similar to the case in which the conceptual model includes a reduced μ range and $\tilde{I}$* does not exceed $75ms^{-1}$ (Figures 8.a and 8.b). Further distinctions between the 2006-2009 GHM period and observations are not possible using the conceptual model due to uncertainty in the gradients of the two regimes (Table 1).

We have proposed a number of diagnostics for comparing observations to the GHM by using a Conceptual Hurricane Intensity Model in which the SST-intensity response is separated into two regimes. To identify areas for forecast model improvement, we hope that these or similar diagnostics may contribute to community-wide projects that compare observations to a broad range of hurricane models in future. By systematically analyzing composite data for hurricanes in observations and models the physical mechanisms underlying ocean-atmosphere interaction during hurricanes can be better understood, which should in the long-term aid the production of better hurricane forecasts.

5. Summary and Discussion

Diagnostics of SST cooling versus hurricane intensity for the GHM compared to observations greatly improve from 2005 to 2006-2009. In 2005, the GHM contains predictions of ocean cooling that are too large for major hurricanes (i.e., category 3 and greater; Figures 3 and 4). In addition, the non-monotonic SST-intensity relationship in observations is absent (Figure 4). From 2006-2009 the GHM performs significantly better compared to observations, both in terms of the magnitude of oceanic cooling and the non-monotonicity of the SST-intensity relationship. The GHM improvements in 2006-2009 compared to 2005 reflect the introduction of warm-core eddies and a representation of the loop current in the Gulf of Mexico, an improved drag-coefficient parameterization, and the addition of Ferrier cloud microphysics.

The 2006-2009 period in the GHM also has good agreement with observations in that decaying storms that are slow moving (or at high latitude, for $V/f < 1$) have larger cooling (Figure 5). Examination of the Gulf of Mexico region and the region east of 80°W indicates that the representation of the loop current and warm core eddies in the GHM are crucial to explaining the improved SST-intensity response for 2006-2009 compared to observations (Figure 7).

One major bias in the GHM is that there is a 0.4K SST cooling over 5.25 days because of a lack of absorption of incoming solar radiation by the ocean component of the GHM. This bias in the model was introduced into the GHM due to excessive warming of the subtropical North Atlantic during boreal summer; the bias is removed in GHM forecasts from 2011 onward (Morris Bender, pers. comm.). The deficiency in incoming solar radiation is in part compensated by enthalpy fluxes that are too large compared to momentum fluxes ($C_h/C_d > 1$; for surface entropy exchange coefficient C_h and surface drag coefficient C_d) in the GHM for both 2005 and 2006-2009 (Morris Bender, pers. comm.). Recent observations indicate that the ratio of enthalpy to momentum fluxes under the Monin-Obukov scale [Monin and Obukhov, 1954] is less than 1 for intensities near hurricane strength and beyond [Powell et al., 2003]. However, the exact value of this ratio is uncertain due to the limited observations in high-wind conditions, and the ratio is an area of active research within the tropical storm community. Assuming that C_h/C_d is too large in both 2005 and 2006-2009 for the GHM compared to observations, one interpretation is that hurricanes in the GHM have too much "growth" due to a strong enthalpy flux (relative to momentum fluxes), which may influence transient intensification and decay phases through a larger intensity growth term (α in the conceptual model framework). Further, the drag coefficient C_d in the GHM model is too large in 2005 and possibly 2006-2009, causing excessive ocean cooling [Walsh et al., 2010]. In their study, Walsh et al. [2010] found that C_d may in fact begin to decrease at a critical intensity, while in the Moon et al. [2004] parameterization, used in the GHM for 2006-2009, C_d tends asymptotically to a constant value. A large value of C_d in the GHM for both time periods examined is also consistent with the diagnosis of excessively strong enthalpy fluxes, giving a larger value of C_h/C_d compared to observations.

A Conceptual Hurricane Intensity Model is presented to provide a framework for the hurricane-induced intensity response (for $V/f < 1$) under two regimes: the first regime driven by atmospheric forcing in which SST cooling increases with intensity; and the second regime controlled by upper oceanic thermal stratification in which SST cooling decreases with intensity, reflecting the observational result that intensification will only produce category 4 and 5 hurricanes when oceanic stratification is weak [Lloyd and Vecchi, 2011]. Observations and the 2006-2009 GHM period compare favorably under the conceptual model framework, while the 2005 GHM period has a monotonic SST-intensity response and only contains the first regime (Figure 8). The 2005 GHM SST-intensity response can be qualitatively matched by the conceptual model by reducing the maximum potential intensity $\tilde{I}$* and, more importantly, only allowing for higher values of oceanic sensitivity μ (Figures 8.a and 8.b). Higher values of μ represent oceanic stratification that is too large in the Gulf of Mexico, since the loop current and warm core eddies are not present in 2005 and excessive SST feedbacks may prohibit intensification.

The conceptual model indicates that the inclusion of low oceanic sensitivity values (μ) representing weaker oceanic stratification is critical to achieving the observed SST-intensity response, and provides an explanation for the model improvement from 2005 to 2006-2009 in the GHM compared to observations. With the improved drag coefficient parameterization [using Moon et al., 2004] starting in 2006 for the GHM, C_d levels off above hurricane intensities corresponding to category 4 and 5. Thus potential intensity, which is proportional to C_k/C_d ([Emanuel, 1988; Bister and Emanuel, 1998]), where C_k represents the enthalpy transfer coefficient, is larger for the most intense hurricanes. In 2005, potential intensity decreases as a function of intensity for the most powerful hurricanes (categories 4 and 5) due to the inverse dependence of C_d on intensity. This inference is supported by lower hurricane intensities for 2005 compared to 2006-2009 (Figure 2). Under the conceptual model framework, hurricanes reach their maximum potential intensity sooner in 2005, and further intensification is strongly dependent on oceanic controls; namely, upper oceanic thermal stratification (Equations 4.1 and 4.2). For intensification to category 4 and 5 storms, oceanic stratification is too strong in the Gulf of Mexico, causing excessive SST feedbacks.

In sum, diagnosis of the SST-intensity response in observations, the GHM, and a conceptual hurricane intensity model show the importance of SST feedbacks on hurricane intensity, and highlight areas of improvement in the GHM. For the GHM, the SST-intensity response is closer to observations after a number of model improvements made for the 2006 forecasts. In particular, the conceptual model indicates that a full range of upper oceanic thermal stratification, representing the loop current and warm core eddies in the Gulf of Mexico is essential in diagnosing the observed SST-intensity response, which can be separated into two regimes: an atmospheric forcing regime at low intensities, and a regime at high intensities in which intensities are close to maximum potential intensity, and oceanic stratification is essential in allowing for further intensification. The parameterization of C_d under Moon et al. [2004] leads to reduced ocean cooling and increased maximum intensity; however, C_d may still be too large for the strongest hurricanes [Powell et al., 2003; Walsh et al., 2010]. In 2005 the second conceptual model regime for oceanic controls dominates for high intensity hurricanes since potential intensity is smaller in the GHM (due to larger C_d). Because oceanic stratification is too strong in the Gulf of Mexico, further intensification of hurricanes is restricted and the SST-intensity response is monotonic.

While rudimentary in nature, the conceptual model provides useful diagnostic tools for operational hurricane forecast models in general, for instance by comparing the gradients of the 95th percentiles in the two conceptual model regimes. More complex versions of the model are possible, for instance through accounting for variable translation speeds, intensification or decay phases, or an attempt to represent the influence of vertical wind shear. Inclusion of these and other factors may produce a more realistic response, but will be more challenging to draw inferences from compared to the simple framework presented. Differences in the SST-intensity response between operational forecast models and observations can thus be identified by examining two regimes in the conceptual model, which may offer insight into forecast model performance and suggest areas for future model improvement.

Acknowledgments. The authors would like to thank Morris Bender, Anand Gnanadesikan, Isaac Held, Stephen Garner, Gabriel Lau, Leo Donner, and Yalin Fan for helpful comments in the preparation of this manuscript. This report was prepared by Ian Lloyd under Award NA08OAR4320752 from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce. The statements, findings, conclusions, and recommendations are those of the authors and do not necessarily reflect the views of the National Oceanic and Atmospheric Administration or the U.S. Department of Commerce.

References

Arakawa, A. and W. H. Schubert, 1974: Interaction of cumulus cloud ensemble with the large-scale environment. part i. *J. Atmos. Sci.*, **31**, 671–701.

Bender, M. A. and I. Ginis, 2000: Real-case simulations of hurricane-ocean interaction using a high-resolution coupled model: effects on hurricane intensity. *Mon. Wea. Rev.*, **128**, 917–946.

Bender, M. A., I. Ginis, R. E. Tuleya, B. Thomas, and T. Marchok, 2007: The Operational GFDL Coupled Hurricane-Ocean Prediction System and a Summary of its Performance. *Mon. Wea. Rev.*, **135**, 3965–3989.

Bister, M. and K. Emanuel, 1998: Dissipative heating and hurricane intensity. *Meteor. Atm. Phys.*, **52**, 233–240.

Blumberg, A. F. and G. L. Mellor, 1987: A description of a three-dimensional coastal ocean circulation model, in three-dimensional coastal ocean models. *N. S. Heaps (Ed.)*, 1–16, American Geophysical Union, Washington, DC, 1987.

Chelton, D. B., S. K. Esbensen, M. G. Schlax, N. Thum, and M. H. Freilich, 2001: Observations of coupling between surface wind stress and sea surface temperature in the eastern tropical pacific. *J. Climate*, **14**, 1479–1498.

Cione, J. J. and E. W. Uhlhorn, 2003: Sea Surface Temperature Variability in Hurricanes: Implications with Respect to Intensity Change. *Mon. Wea. Rev.*, **131**, 1783–1796.

DeMaria, M., M. Mainelli, L. K. Shay, J. A. Knaff, and J. Kaplan, 2005: Further Improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Wea. Forecasting*, **20**, 531–543.

Emanuel, K. A., 1988: The maximum intensity of hurricanes. *J. Atmos. Sci.*, **45**, 1143–1155.

Ezer, T. and G. L. Mellor, 1997: Simulations of the atlantic ocean with a free surface sigma coordinate ocean model. *J. Geophys. Res.*, **102**, 15 647–15 657.

Ferrier, B. S., 2005: An efficient mixed-phase cloud and precipitation scheme for use in operational nwp models. *Eos, Trans. Amer. Geophys. Union*, **86**, (Spring Meeting Suppl.), Abstract A42A–02.

Gopalakrishnan, S., Q. Liu, T. Marchok, D. Sheinin, N. Surgi, R. Tuleya, R. Yablonsky, and X. Zhang, 2010: Hurricane Weather Research and Forecasting (HWRF) Model Scientific Documentation. Tech. rep.

Jin, F.-F., 1997: An equatorial ocean recharge paradigm for enso. part i: Conceptual model. *J. Atmos. Sci.*, **54**, 811–829.

Kalnay, E., et al., 1996: The NMC/NCAR 40-year reanalysis project. *Bull. Am. Meteorol. Soc.*, **77**, 437–471.

Kaplan, J. and M. DeMaria, 2003: Large-Scale Characteristics of Rapidly Intensifying Tropical Cyclones in the North Atlantic Basin. *Wea. Forecasting*, **18**, 1093–1108.

Kimball, S. K. and M. S. Mulekar, 2004: A 15-Year Climatology of North Atlantic Tropical Cyclones. Part I: Size Parameters. *J. Climate*, **17**, 3555–3575.

Knapp, K. R., M. C. Kruk, D. H. Levinson, and E. J. Gibney, 2009: Archive compiles new resource for global tropical cyclone research. *Eos, Transactions, AGU.*, **90**, doi:10.1029/2009EO060002.

Knutson, T., R. E. Tuleya, W. Shen, and I. Ginis, 2001: Impact of CO2-Induced Warming on Hurricane Intensities as Simulated in a Hurricane Model with Ocean Coupling. *J. Climate*, **14**, 2458–2468.

Kurihara, Y., R. E. Tuleya, and M. A. Bender, 1998: The GFDL Hurricane Prediction System and its performance in the 1995 hurricane season. *Mon. Wea. Rev.*, **126**, 1306–1322.

Large, W. G. and S. Pond, 1981: Open ocean momentum flux measurements in moderate to strong wind. *J. Phys. Oceanogr.*, **11**, 324–336.

Lloyd, I. D. and G. A. Vecchi, 2011: Observational evidence for oceanic controls on hurricane intensity. *J. Climate*, **24**, 1138–1153.

Monin, A. S. and A. M. Obukhov, 1954: Basic laws of turbulent mixing in the surface layer of the atmosphere. *Tr. Geofiz. Inst. Akad. Navk SSSR*, **24**, 163–187.

Moon, I.-J., I. Ginis, and T. Hara, 2004: Effect of surface waves on charnock coefficient under tropical cyclones. *Geophys. Res. Lett.*, **31**, L20 302, doi: 1029/2004GL020988.

Powell, M. D., P. J. Vickery, and T. A. Reinhold, 2003: Reduced drag coefficient for high wind speeds in tropical cyclones. *Nature*, **422**, 279–283.

Schade, L. and K. Emanuel, 1999: The Ocean's Effect on the Intensity of Tropical Cyclones: Results from a Simple Coupled Atmosphere-Ocean Model. *J. Atmos. Sci.*, **56**, 642–651.

Sela, J., 1980: Spectral modeling at the national meteorological center. *Mon. Wea. Rev.*, **45**, 1279–1292.

Shen, W. and I. Ginis, 2003: Effects of surface heat flux-induced sea surface temperature changes on tropical cyclone intensity. *Geophys. Res. Lett.*, **30**, 3863–3866, doi:10.1029/2003GL017878.

Smith, T. M. and R. W. Reynolds, 2003: Extended reconstruction of global sea surface temperatures based on COADS data (1854-1997). *J. . Climate*, **16**, 1495–1510.

Tang, B. and K. A. Emanuel, 2010: The maximum intensity of hurricanes. *J. Atmos. Sci.*, **67**, 1817–1830.

Environmental Modeling Center, 2003: The gfs atmospheric model. *NCEP Office Note 442. Global Climate and Weather Modeling Branch, EMC, Camp Springs, MD.*, [Also available online at:http://www.emc.ncep.noaa.gov/officenotes/new

Vecchi, G. A. and B. Soden, 2007: Effect of remote sea surface temperature change on tropical cyclone potential intensity. *Nature*, **450**, 1066–1070, doi: 10.1038/nature06423.

Walsh, K. J. E., P. Sandery, G. B. Brassington, M. Entel, C. Siegenthaler-LeDrian, J. D. Kepert, and R. Darbyshire, 2010: Constraints on drag and exchange coefficients at extreme wind speeds. *J. Geophys. Res.*, **115**, C09 007, doi:10.1029/2009JC005876.

Wentz, F. J., C. Gentemann, D. Smith, and D. Chelton, 2000: Satellite measurements of sea surface temperature through clouds. *Science*, **288**, 847–850.

Xie, S.-P., M. Ishiwatari, H. Hashizume, and K. Takeuchi, 1998: Coupled ocean-atmospheric waves on the equatorial front. *Geophys. Res. Lett.*, **25**, 3863–3866.

Yablonsky, R. and I. Ginis, 2008: Improving the ocean initialization of coupled hurricane ocean models using feature-based data assimilation. *Mon. Wea. Rev.*, **136**, 2592–2607.

[Appendix A: Conceptual Hurricane Intensity Model] We wish to develop a conceptual model of hurricanes to reproduce the observed SST-intensity response and examine the role of negative oceanic feedback on hurricanes. First, we assume that hurricane intensity I (ms^{-1}) varies with time t according to:

$$\frac{\partial I}{\partial t} = \alpha(I^* - I) \tag{.1}$$

Where I^* is a maximum potential intensity. The potential intensity could be, but is not confined to, the Emanuel [1988] potential intensity. Any theoretical or empirical measure representing the true value of maximum storm intensity could represent the potential intensity I^*. The α constant is an inverse growth term, with units of days^{-1}. To first order we assume that hurricane potential intensity can be linearized as follow:

$$I^* = \tilde{I}* - \beta T \tag{.2}$$

Where $\tilde{I}*$ represents the pre-storm potential intensity value – that is, the intensity before passage of a storm over a particular location – for instance on day -2. The βT term represents a reduction in the intensity when a cyclone passes over a point on the ocean surface with an SST cooling anomaly of magnitude T (for instance $T = +1K$ represents an SST cooling of $1K$). The constant linearization term β ($ms^{-1}K^{-1}$) represents a reduction in intensity for one degree of ocean cooling, and can be estimated from observations (see Appendix B). Combining Equations .1 and .2 we arrive at an atmospheric equation for hurricane intensity:

$$\frac{\partial I}{\partial t} = \alpha(\tilde{I}* - I - \beta T) \tag{.3}$$

We couple Equation .3 for the atmosphere to an oceanic equation, showing the response to cyclone forcing and subsequent recovery:

$$\frac{\partial T}{\partial t} = \mu I - \epsilon T \tag{.4}$$

The μI term represents cooling due to cyclonic winds and cyclone induced changes to net-air sea fluxes. The oceanic sensitivity parameter μ scales as a temperature change per unit of vertical depth, and is in units of $(Ks^{-1})/(ms^{-1})$. The ϵT term represents a restoring term, so that the cooling T with return to a value of zero, and SST returns to climatology after an e-folding time of ϵ^{-1}, where ϵ is in units of days^{-1}.

Further assumptions are needed to make progress. First, we take our model as being one-dimensional, with hurricanes moving along a path with translation speed C (schematic shown in Figure 9). A translation speed of $2.3ms^{-1}$ is used for the steady state SST-intensity response presented in this paper. This value represents a middle-range translation speed in the slow-moving / high latitude regime of $V/f < 1$ in which oceanic controls are important [Lloyd and Vecchi, 2011]. We assume that hurricanes are axisymmetric and that the radial profile of a hurricane follow the Rankine vortex, such that the radial intensity structure of a hurricane is given by:

$$I(x,t) = I_m(t).R(x - ct) \tag{.5}$$

Where $I(x,t)$ is the hurricane intensity at position x and time t, $I_m(t)$ is the maximum intensity of a hurricane along its radial profile at a given time, and $R(x - ct)$ represents the spatial distribution of hurricane intensity, which follows:

$$V = \begin{cases} V_0.(r/R_{max}) & \text{r} \leq R_{max} \\ V_0.(r/R_{max})^{-1} & R_{max} < \text{r} \leq 6R_{max} \\ 0 & \text{r} > 6R_{max} \end{cases} \tag{.6}$$

The Rankine Vortex profile can be seen in Figure 10. We choose R_{max} to be 80km [Kimball and Mulekar, 2004]. The cutoff at $6R_{max}$ in Equation .6 is arbitrary; however, we are not interested in the exact numerical values of the solution. The $6R_{max}$ cutoff indicates that at a certain point beyond the hurricane center, the hurricane winds will be indistinguishable from background atmospheric winds.

In order to use Equations .1-.6 to make numerical calculations we further assume that the atmospheric model will only feel the mean SST change underneath the cyclone. This coarse method allows for a first order approximation to the net effect of ocean cooling on a hurricane. Modifying Equations .3 and .4 gives the coupled equations for cyclone induced cooling T and maximum intensity I_m:

$$\frac{\partial I_m(t)}{\partial t} = \alpha(\tilde{I}* - I_m(t) - \beta < T(x,t) >) \tag{.7}$$

$$\frac{\partial T(x,t)}{\partial t} = \mu I(x,t)W(x-ct) - \epsilon T(x,t) \tag{.8}$$

Where $< T(x,t) >$ indicates average SST cooling under the hurricane, and $W(x-ct)$ is a weight function that represents the two-dimensional nature of hurricanes on the horizontal plane:

$$W(x-ct) = \sqrt{1 - \frac{(x-ct)^2}{(6R)^2}} \tag{.9}$$

The weight function is largest at the center of the hurricane ($x = ct$), which is the point where the hurricane reaches its maximum radius ($6R_{max}$) perpendicular to the direction of hurricane translation. Moving away from the center of the hurricane along the direction of translation, the weight function tends to zero as the perpendicular extend of the hurricane becomes smaller, so that the hurricane has least impact on SST cooling at its outer boundary.

[Appendix B: Parameter estimation from observations for the Conceptual Hurricane Intensity Model]

Equations .7 and .8 can be used to calculate the SST-intensity response. It is desirable to constrain the five model parameters, α, β, μ, ϵ, and $\tilde{I}*$ as fully as possible in order to try and reproduce conditions which are approximate to the real world.

The growth term α is hard to estimate from observations, and is taken to be 0.5 (two day timescale) as a reasonable value. However, the value of α only affects intensification and decay phases for hurricanes. The steady state solution of the SST-intensity response, which is analyzed in this paper, is independent of α. An estimate of β is taken from Vecchi and Soden [2007] as $\beta = 8.2ms^{-1}.K^{-1}$. This estimate was calculated from a linear regression fit in June-November using IPCC-AR4 multi-model ensemble using Emanuel's Maximum Potential Intensity (MPI) formulation [Emanuel, 1988], a result that is confirmed by reanalysis data [Kalnay et al., 1996; Smith and Reynolds, 2003]. To estimate ϵ, we assume that the SST cooling recovers with the same time scale in all oceans (this assumption was found to hold approximately true in all ocean basins). We then take ϵ as the inverse of the e-folding timescale, which is found to be 0.19 (Figure 11).

Our remaining variables μ and $\tilde{I}*$ are free parameters. We take $\tilde{I}*$ to vary from 15 to 80 ms^{-1}, in order to simulate observations of maximum tropical cyclone intensities. The variable μ is estimated to vary from 0 to 0.09, which is derived from scaling arguments. For instance a $T = +1K$ change in one day for a $50ms^{-1}$ storm gives $\mu = 0.02$. A value of $\mu = 0$ represents the limit in which temperature is invariant with depth. The steady-state I and T profiles are shown for standard parameter values in Figure 12, for translation speeds of $2.3ms^{-1}$ ("slow") and $6.3ms^{-1}$ ("fast"). In the slow-moving case, the SST cooling response is larger and, because of an increased negative SST-feedback, the maximum intensity I_m is reduced compared to the "fast" moving case.

Table 1: Linear regression slopes for the two regimes (Gradients I and II) defined in the Conceptual Hurricane Intensity Model framework. The slope and uncertainty from linear regression lines for the two regimes are shown for observations from 1998-2009, the GHM in 2005, and the GHM for 2006-2009. Uncertainty in the gradient values is given at the 95% confidence level, calculated using the standard error and t-statistic. Percentage values in brackets indicate correlations. Gradient II does not exist for the GHM in 2005, since the SST-intensity response is monotonic (see Figure 8.b).

	Observations (1998-2009)	GHM (2005)	GHM (2006-2009)
Gradient I ($-\mu/\epsilon$) ($10^{-1} K m^{-1} s^{-1}$)	-1.03 ± 0.65 (97.8%)	-1.26 ± 0.19 (90.4%)	-1.33 ± 0.78 (93.5%)
Gradient II ($+1/\beta$) ($10^{-1} K m^{-1} s^{-1}$)	$+0.67 \pm 0.32$ (90.5%)	n/a	$+0.54 \pm 0.37$ (91.6%)

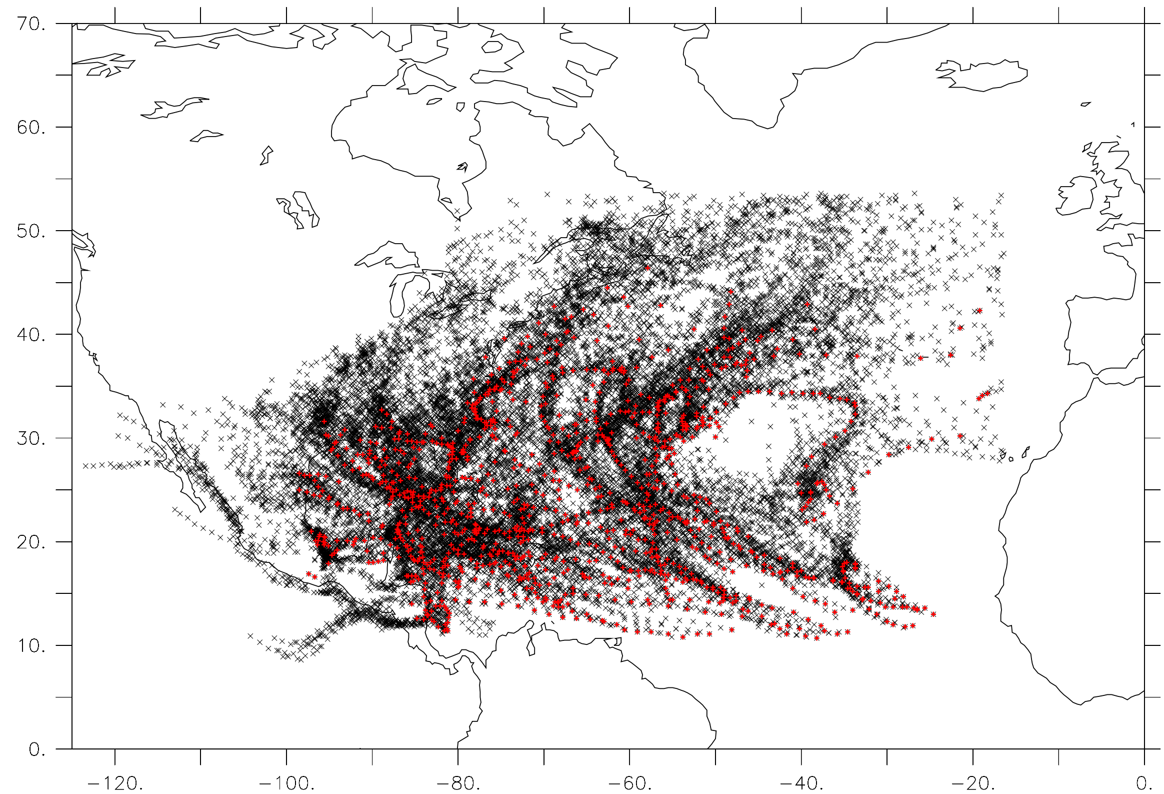

Figure 1: GFDL Hurricane Forecast Model (GHM) storm tracks, for 2005-2009. Red points indicate initial forecast positions, while black points indicate hurricane forecast locations at six hour intervals up to 126 forecast hours.

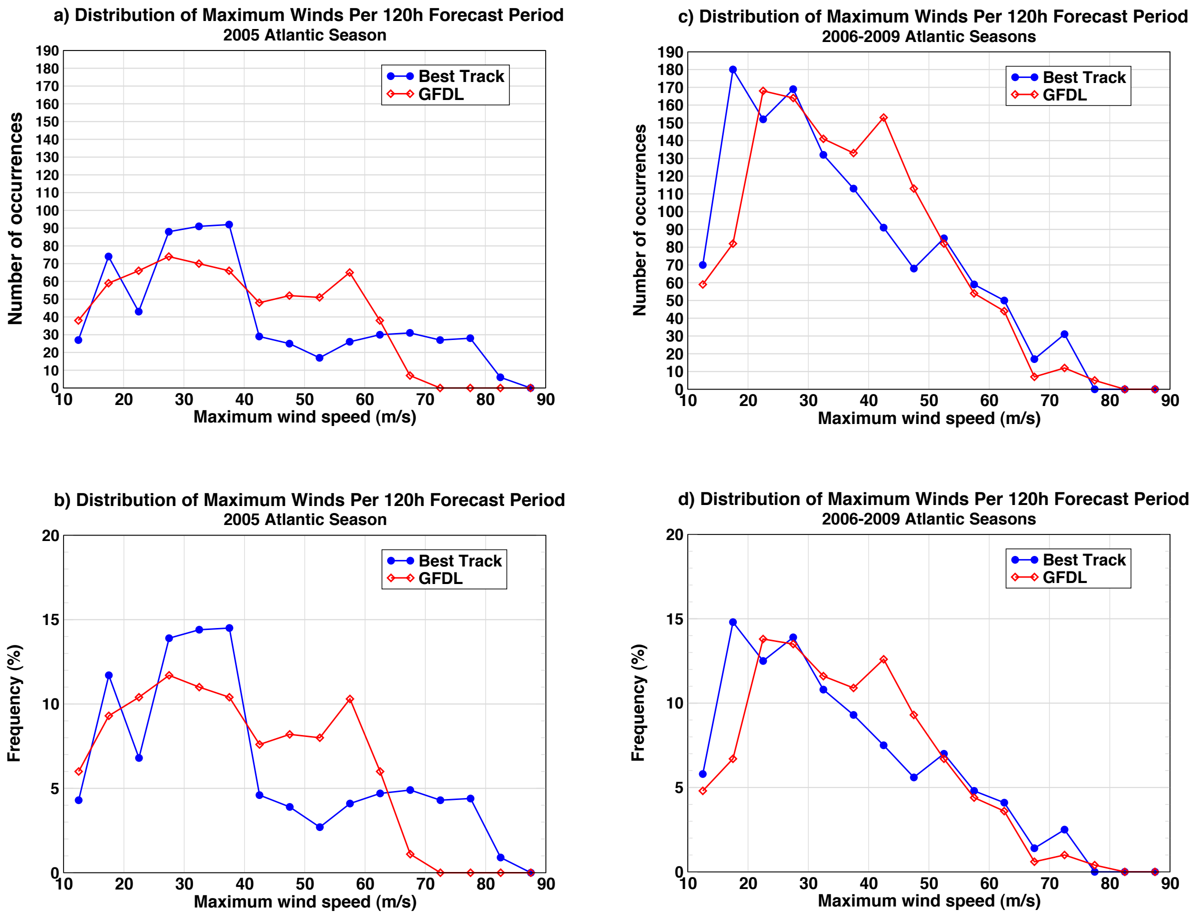

Figure 2: Distribution of intensity (denoted by maximum wind speed; $m.s^{-1}$) for all North Atlantic storms in 2005 and 2006-2009. The GFDL Huricane Forecast Model (GHM) is marked in red, while the National Hurricane Center Best Track Data for observations is marked in blue. a) and c) indicate number of occurrences (y-axis) versus intensity (x-axis), while b) and d) indicate frequency of occurrences (y-axis) versus intensity (x-axis), for 2005 and 2006-2009 respectively.

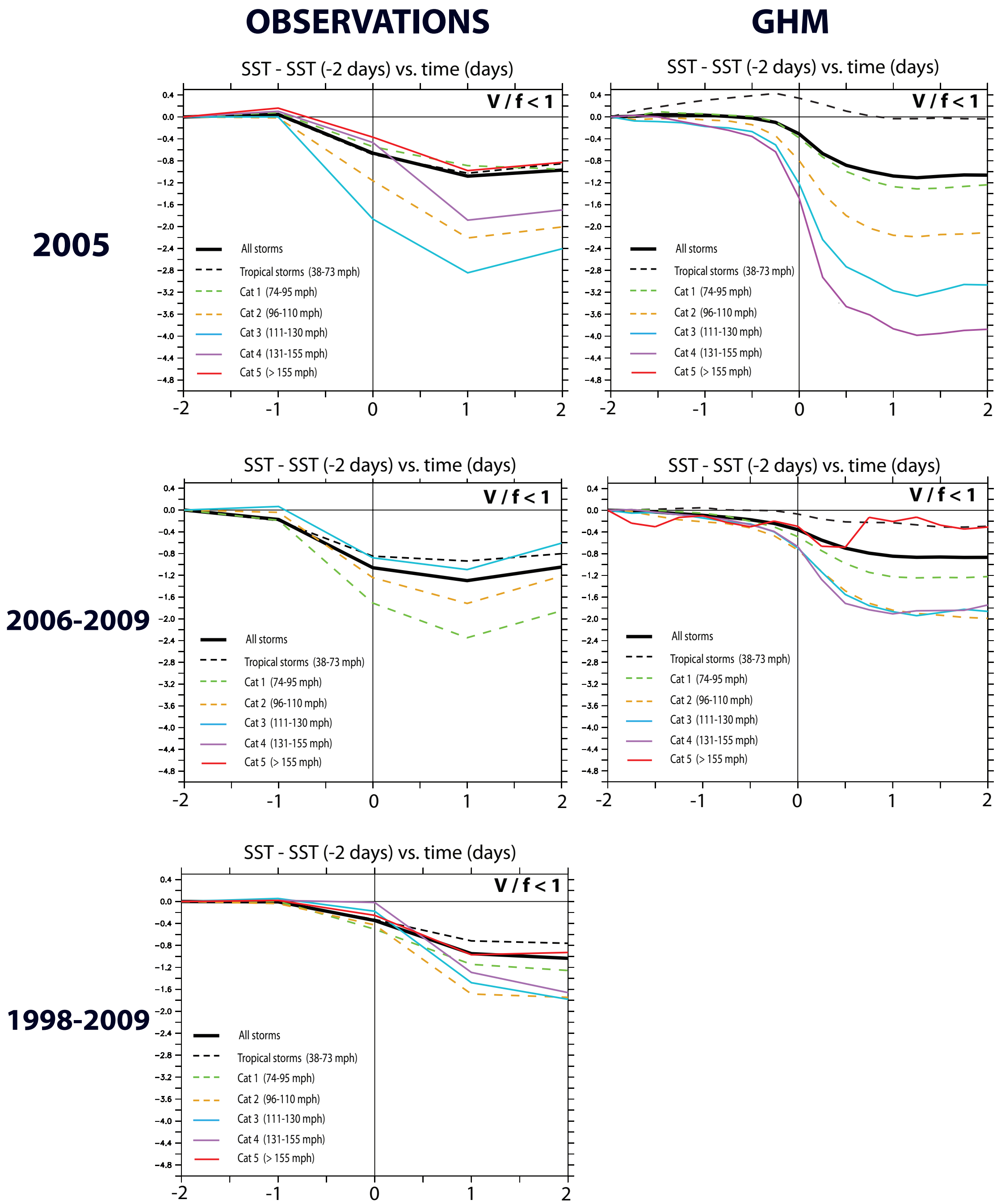

Figure 3: Lagrangian composite plots of hurricane-induced SST change (units of K on the y-axis) versus time (units of days on the x-axis) relative to SST on day -2. Composite plots are shown for $V/f < 1$, where 1 unit $= 100km$, for slow moving (or high latitude) storms. Day 0 represents the time at which a hurricane passes a given location. Shown for observations (left panels) and the GHM (right panels) for the periods 2005 and 2006-2009. Observations are also shown for 1998-2009 (bottom-left).

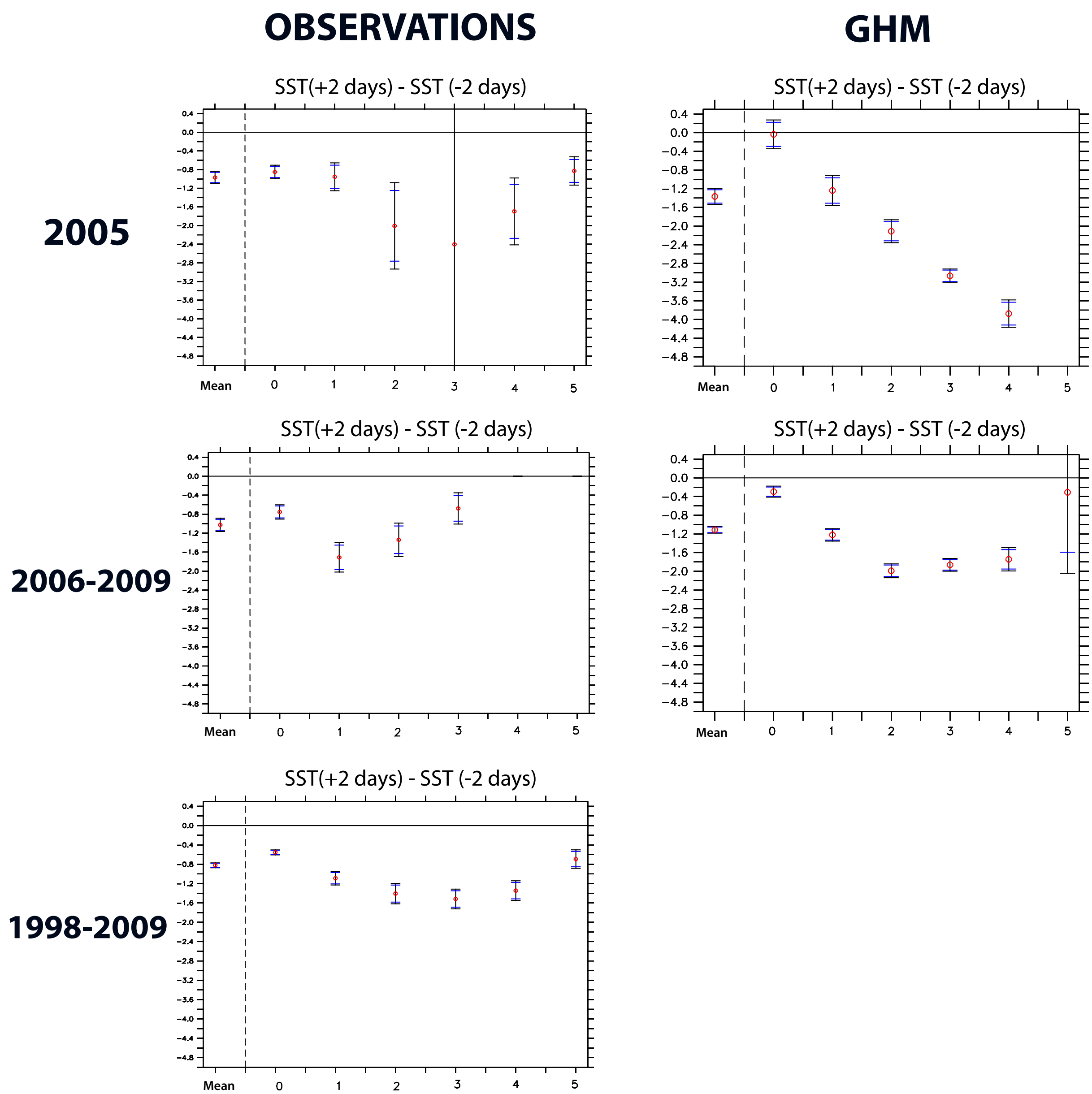

Figure 4: Comparison of observations and the GHM for 2005 and 2006-2009, for the criteria $V/f < 1$. SST change on day +2 relative to day -2 is shown on the y-axis, with error bars marking to 90% and 95% confidence intervals in the mean. The data point on the far left indicates the mean composite response for all tropical cyclones, while other points mark different categories on the Saffir-Simpson scale, indicated by numbering along the x-axis. Observations are also shown for 1998-2009.

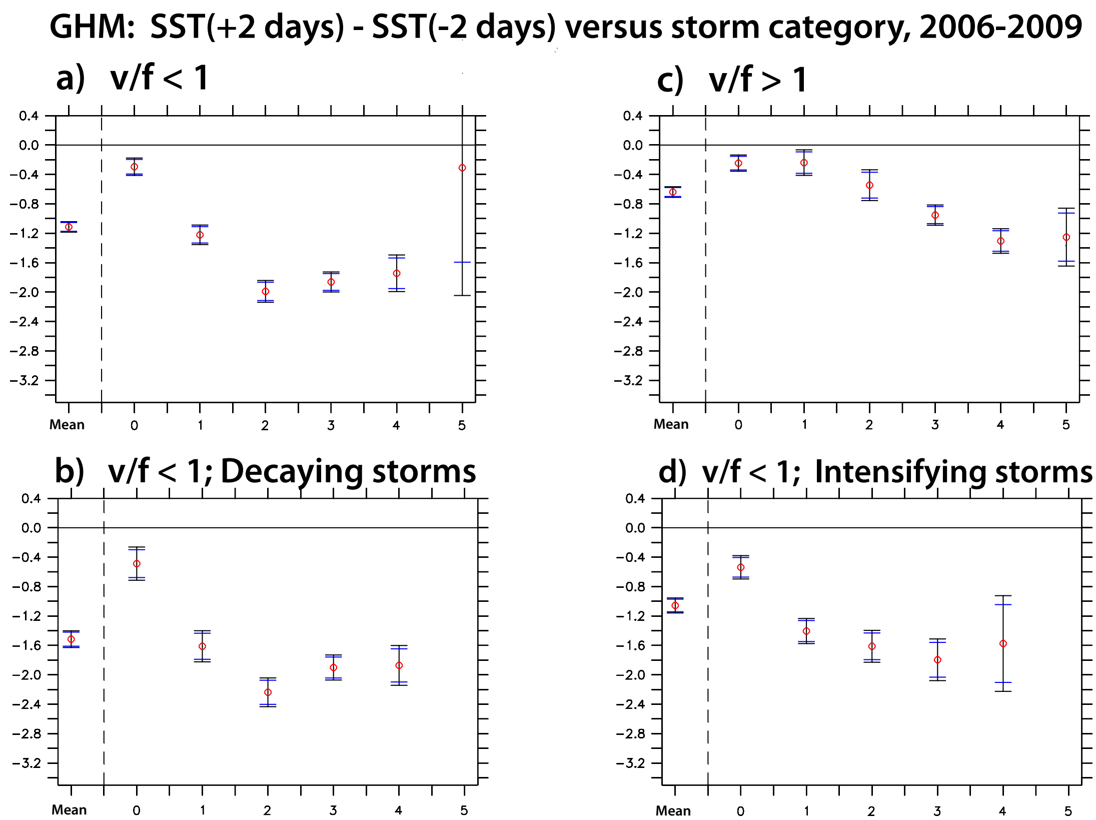

Figure 5: Diagnostics of the GHM SST-intensity response for 2006-2009, with hurricane-induced SST change for day +2 minus day -2 shown on the y-axis, and storm category on the Safir-Simpson scale indicated on the x-axis. a) and c) show the SST-intensity response for the criteria $V/f < 1$ (slow moving / high latitude) and $V/f > 1$ (fast moving / low latitude) respectively. b) and d) show the response for decaying and intensifying storms, for the criteria $V/f < 1$

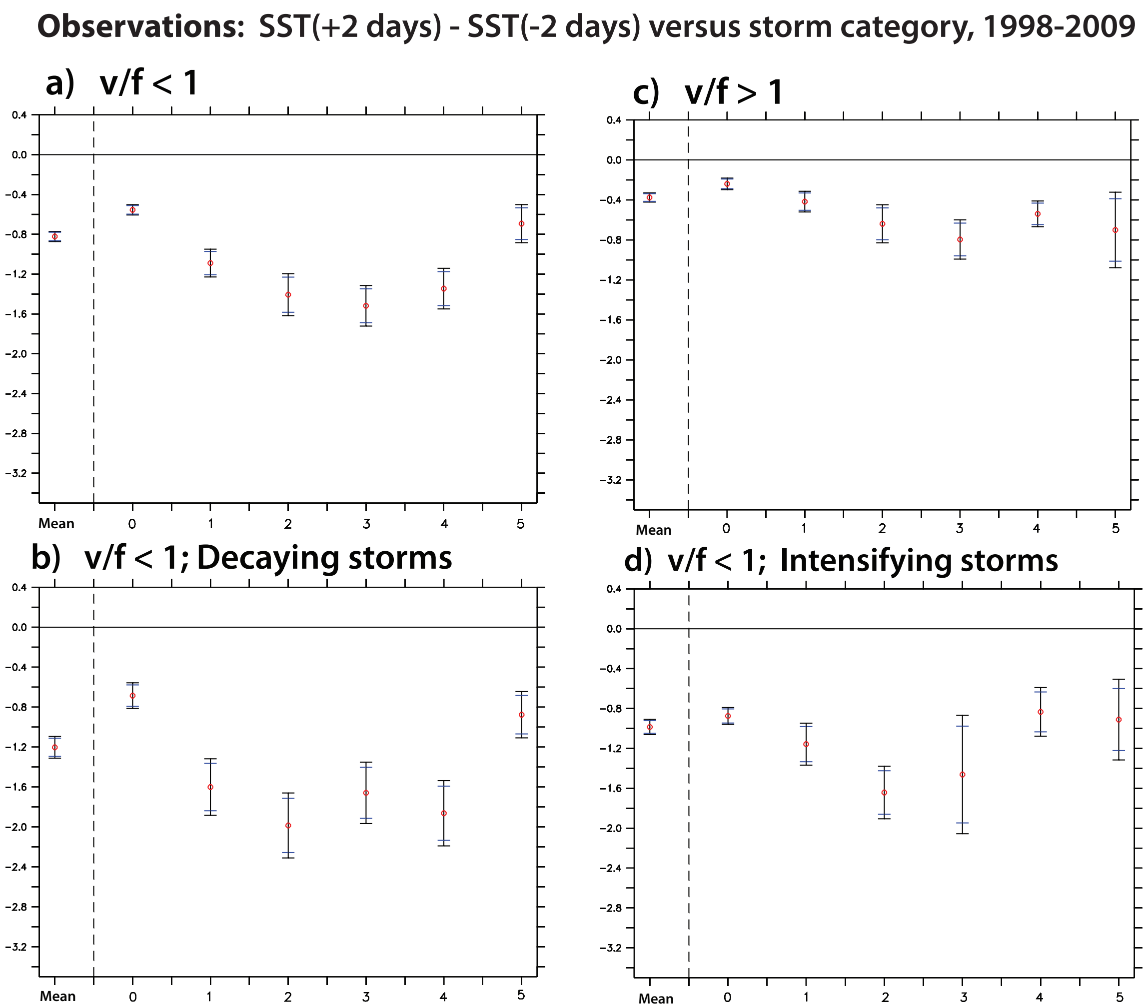

Figure 6: Same as Figure 5, but for observations from 1998-2009.

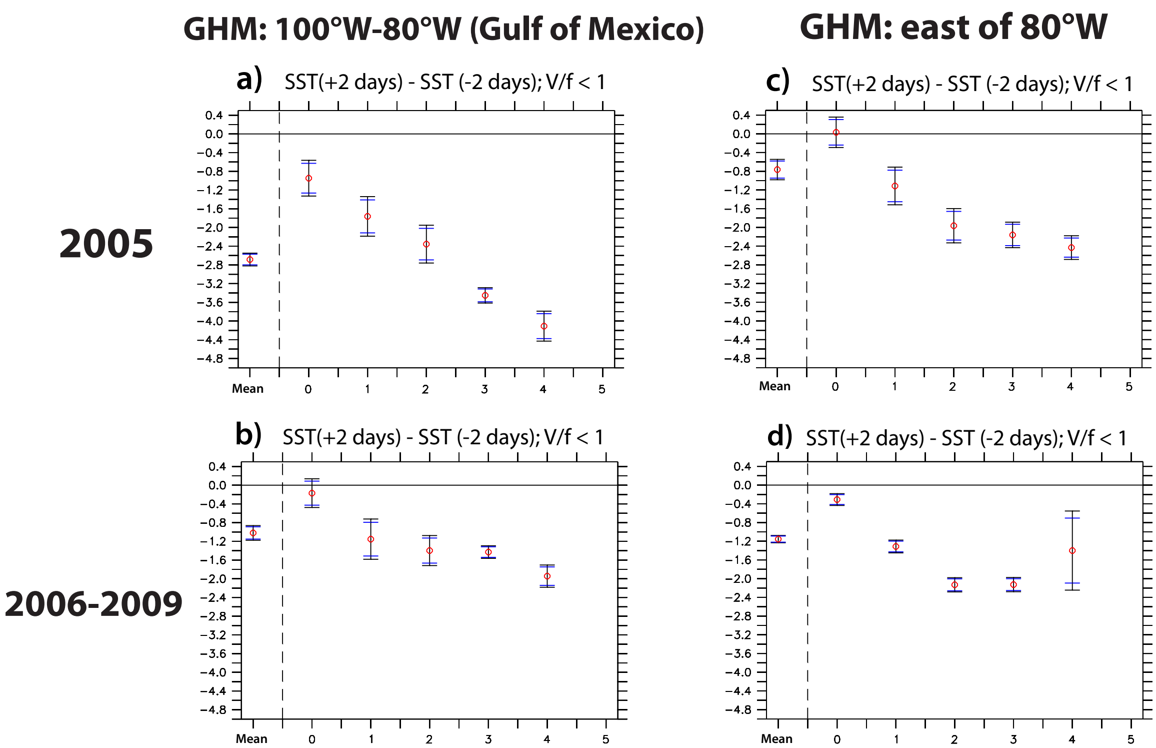

Figure 7: GHM SST-intensity response for 2005 and 2006-2009, showing geographic subdivisions in the North Atlantic. a) and b) show the SST-intensity response for GHM forecast data between 100°W - 80°W, capturing the Gulf of Mexico region. c) and d) indicate the SST-intensity response for forecasts east of 80°W, outside the Gulf of Mexico.

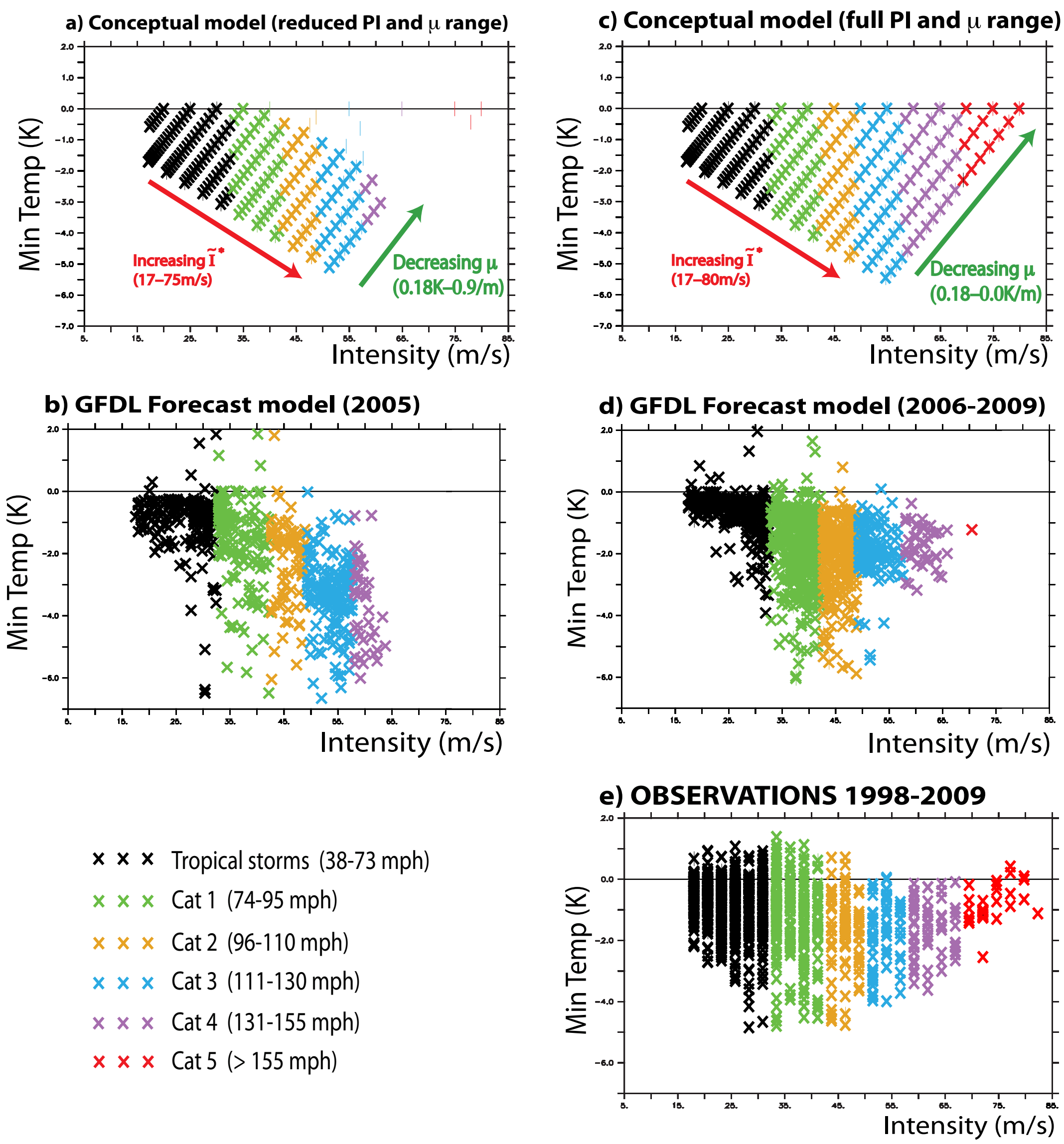

Figure 8: Comparison of the SST-intensity response for the conceptual hurricane intensity model, GHM from 2006-2009, and observations for 1998-2009, with the criteria $V/f < 1$. The y-axis shows hurricane-induced SST cooling (K) for day +2 relative to day -2, while the x-axis shows maximum wind speed (ms^{-1}). Colors indicate hurricane category on the Saffir-Simpson scale (see key in top-left panel).

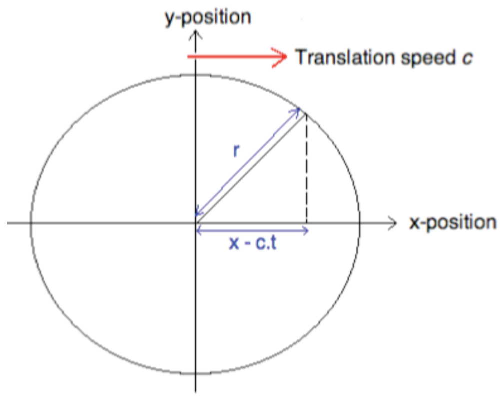

Figure 9: Conceptual Hurricane Intensity Model: representation of an axisymmetric hurricane moving with translation speed C along the x-axis in the horizontal plane.

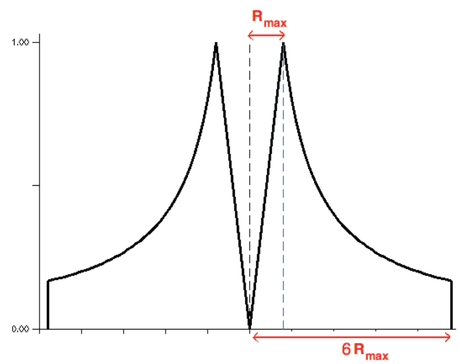

Figure 10: Conceptual Hurricane Intensity Model: Rankine Vortex profile for the radial hurricane intensity distribution. Intensity is indicated on the y-axis, while the x-axis indicates radial distance from the hurricane center (at $V = 0$), with a peak at R_{max} and maximum radius of $6R_{max}$.

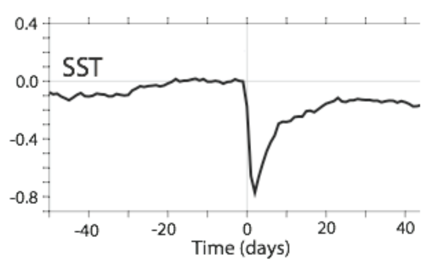

Figure 11: Lagrangian composite of the SST-intensity response, showing an e-folding timescale of 5.2 days. Composite time is on the x-axis, with day 0 representing the time at which a hurricane passes a fixed location. Hurricane-induced SST cooling is shown on the y-axis.

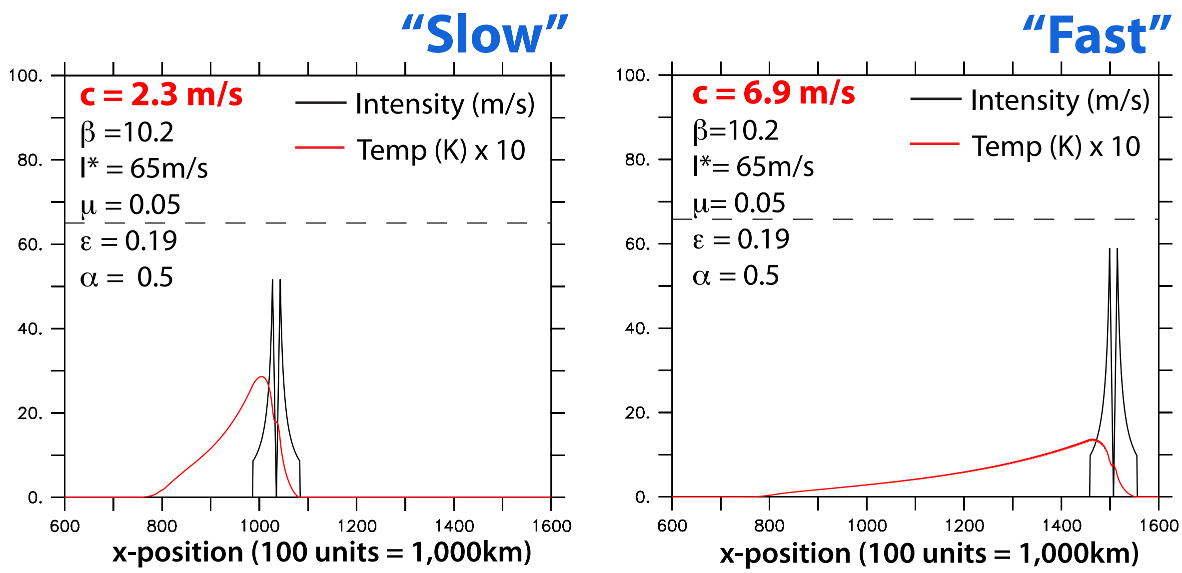

Figure 12: Conceptual Hurricane Intensity Model: Intensity and SST cooling profiles for the steady-state response of slow and fast moving hurricanes ($2.3ms^{-1}$ and $6.9ms^{-1}$ respectively). The black profile indicates the intensity distribution (ms^{-1}) while the red profile indicates T, the magnitude of hurricane-induced SST cooling (10^1K). The x-axis represents position along the direction of hurricane translation, with parameter values listed in the figure. The black dashed line indicates the value of maximum potential intensity, I^*.